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<p>The long-term goals of this project are to understand the physical oceanographic circulation processes on continental shelves with emphasis on the mechanisms involved in across-shelf transport. The scientific objectives include the application of numerical circulation models to process studies and to simulations of continental shelf fields, including the nearshore surf zone, to help achieve understanding of the flow dynamics. The numerical experiments are supplemented with analytical studies whenever possible. Overall, considerable progress was made toward these objectives with notable contributions in several areas. Some examples are the following. New results were obtained for downwelling flow fields including information about vertically well-mixed regions nearshore, downwelling fronts, and symmetric instabilities in the bottom boundary layer. Bottom boundary layer flows on the shelf under downwelling conditions were shown in general to be susceptible to the occurrence of symmetric instabilities. Results of studies of instabilities of alongshore currents over plane beaches show the nonlinear evolution of shear instabilities, after initial growth at the wavelength of the most unstable linear mode, into new larger-wavelength, propagating, unsteady disturbances. Results with sand bar topography point to the possible existence in the nearshore surf zone of an energetic eddy field associated with instabilities of the alongshore current.</p>				
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## FINAL TECHNICAL REPORT

ONR GRANT N00014-93-1301

### **Title: Modeling of Coastal Ocean Flow Fields**

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## **LONG-TERM GOALS**

To understand the dynamics of physical oceanographic circulation processes on continental shelves and slopes with emphasis on the mechanisms involved in across-shelf transport.

## **SCIENTIFIC OBJECTIVES**

To apply numerical circulation models to process studies and to simulations of continental shelf and slope flow fields, including the nearshore surf zone, to help achieve understanding of the flow dynamics.

## **APPROACH**

Numerical finite-difference models based on the primitive equations, balance-type intermediate equations, and the shallow-water equations are applied to two- and three-dimensional flow problems relevant to the dynamics of continental shelf and slope flow fields. The Blumberg-Mellor sigma coordinate Princeton Ocean Model POM model is utilized for studies with the primitive equations. A shallow-water equation model has been developed and applied to studies involving vorticity dynamics of currents in the nearshore surf zone. The numerical experiments are supplemented with analytical studies whenever possible.

## **RESULTS**

The results of the research supported by this grant are reported in the publications listed at the end of this section. Some of the primary results are summarized briefly below.

The idealized response studies of flow on the Oregon continental shelf show interesting new features of downwelling flow fields. The characteristics of the downwelling circulation (Allen and Newberger, 1996) differ considerably from those found during upwelling. The dominant feature of the response flow field is a downwelling front that moves slowly offshore, leaving behind an inshore region where the density is well mixed. The downwelling front in the alongshore velocity extends over the full depth and is nearly vertical, separating relatively weak alongshore velocities nearshore from a stronger coastal jet offshore. The front contains strong vertical motion from the surface to the bottom and some recirculation. Much of the offshore flow from the base of the front is characterized by time- and space-dependent fluctuations involving spatially periodic separation and reattachment of the bottom boundary layer and accompanying recirculation cells. The flow in this layer has positive potential vorticity and has

been identified as resulting from finite amplitude symmetric instabilities (also called slantwise convection).

The studies concerning the propagation of near-inertial waves (Federiuk and Allen, 1996) show the behavior is strongly dependent on the structure of the alongshore velocity field and the density field. Forcing with the observed upwelling-favorable wind stress from summer 1973 leads to the presence of substantial near-inertial wave energy over the shelf. In contrast, the same wind stress with the sign reversed (which does not change the efficiency of near-inertial wave generation) results in downwelling conditions that are accompanied by almost no near-inertial wave energy over the shelf. Also, comparable experiments using linear equations (which do not include interactions of the waves with the background flow) give different, incorrect results showing little inertial wave energy over the shelf for either upwelling or downwelling winds. Analysis of velocity measurements from the Oregon continental shelf support the model results.

The studies comparing the accuracy of the Boussinesq equations, the reduced system, and the primitive equations (Newberger and Allen, 1996) show that a semi-implicit formulation of the Boussinesq equations results in smaller errors than the reduced system for comparable computational effort.

In Allen and Holm (1996) it was shown that, by varying the expansion utilized in Hamilton's Principle a family of different approximate Hamiltonian models could be derived. For each member of the family the functional form of the potential vorticity, conserved on fluid particles, and of the kinetic energy contribution to the globally conserved energy can be prescribed. A particular new model with higher order dynamical consistency, and thus likely increased accuracy, is derived. In Allen, Gent, and Holm (1997), it is found that, compared with other proposed boundary conditions for the balance equations, the boundary conditions derived in Allen (1991) give the most accurate approximate solutions for Kelvin waves.

A linear stability analysis of the steady, inviscid, two-dimensional, "arrested Ekman layer" (Allen and Newberger, 1998) shows that this flow is unstable to symmetric instabilities and confirms that a necessary condition for instability is positive potential vorticity in the bottom layer. Numerical experiments show that for two-dimensional initial-value problems the unstable, time-dependent, nonlinear behavior in the boundary layer involves the formation of slantwise circulation cells with characteristics similar to those found in the wind-forced downwelling circulation.

In the study of nonlinear shear instabilities of alongshore currents in the surf zone over plane beaches (Allen, Newberger and Holman, 1996), the nature of the flow depends on a dimensionless parameter  $Q$ , which is the ratio of an advective to a frictional time scale. For  $Q$  above a critical value, instabilities develop. A robust characteristic of these instabilities is the rapid evolution, after initial growth at the wavelength of the most unstable linear mode, into larger-wavelength, nonlinear, propagating, unsteady wavelike disturbances. In contrast, with shore-parallel sand bar topography and with forcing from a wave-transformation submodel, as  $Q$  is increased, the flow becomes increasingly unsteady exhibiting a transition from equilibrated shear waves to a turbulent shear flow (Slinn, Allen, Newberger, and Holman, 1998). The results with alongshore-uniform sand bar topography point to the possible existence in the nearshore surf zone of an energetic eddy field associated with instabilities of the alongshore current.

Results from experiments with alongshore variable sand bars (Slinn, Allen, and Holman, 1999) show significant influence of alongshore topographic variability on the nearshore circulation. In particular, one notable feature is the tendency for contours of both the time mean and the root mean square vorticity fields to align along contours of constant depth.

A new, approximate, extended-geostrophic model for balanced, rotating, stratified motion governed by the primitive equations has been systematically derived by using a small Rossby number expansion in Hamilton's Principle (Allen, Holm, and Newberger, 2002). Results of numerical experiments concerning instability of a baroclinic jet show that the new extended-geostrophic model gives accurate approximate solutions to the primitive equations with errors substantially smaller than found with either a quasi-geostrophic or a geostrophic momentum model.

In a modeling study of turbulent mixing over the continental shelf (Wijesekera et al., 2002), the following results were found. During upwelling favorable winds, the majority of turbulent mixing occurs in the top and the bottom boundary layers and in the vicinity of the vertically and horizontally sheared coastal jet. Turbulent mixing in the coastal jet is primarily driven by shear-production, which is stronger on the shoreward side of the jet than on the offshore side. The near-surface flow on the inner-shelf becomes convectively unstable as wind stress forces the upwelled-water to flow offshore in a turbulent surface layer. During downwelling favorable winds, the strongest mixing occurs in the vicinity of the downwelling front. The offshore side of the front is stratified and turbulent mixing is weak. The shoreward side is well mixed and turbulent mixing is strong. The largest turbulent kinetic energy  $TKE$  and dissipation of  $\epsilon$  are found near the bottom of the front. Turbulence in the bottom boundary layer offshore of the front is concentrated between re-circulation cells which are generated as a result of symmetric instabilities in the boundary layer flow. Here  $TKE$  is generated by shear production.

Research has been pursued on modeling studies for inner shelf flow fields by considering the wind-forced circulation off Duck, NC in August-November 1994 during the time of the Coastal Ocean Processes (CoOP) field experiment. This is part of Ph.D. thesis research by Brandy T. Kuebel that is still in progress. For the initial numerical experiments, the assumption of alongshore uniform two-dimensional flows, with spatial variations in the across-shelf ( $x$ ) and vertical ( $z$ ) directions, is utilized. The model is forced by observed wind stress and heat flux. During the time period of the field experiment and the model calculations, both stratified (August) and unstratified (October-November) conditions exist allowing comparison of the shelf flow response in these two different regimes. Objectives include determination of the nature of the across-shelf circulation. The model-produced alongshore velocities are well correlated with current measurements from the CoOP field experiment providing confidence in the model results. Comparison between stratified (August) and nonstratified (October) regimes shows marked differences in the across-shelf transport with substantial reduction, relative to predicted Ekman transport calculated from the wind stress, near the coast during nonstratified conditions. Model dynamical balances have been analyzed and utilized to explain these qualitative differences in the circulation. Following the initial focus on the characteristics of the Eulerian model fields, attention has been given to a study of fluid particle motion from the Lagrangian perspective. Two different techniques have been employed to track particles. A Lagrangian drifter method uses a fourth-order Runge Kutta scheme to track particles at each model time step and a conservative tracer technique that advects three different tracers (to represent the three initial coordinates of fluid particles) using the model velocities and a higher-order Smolarkiewicz

advection scheme. New results are found regarding net vertical and horizontal particle displacements during the two different regimes in August and September.

Mesoscale circulation in the Gulf of California has been studied with numerical model experiments utilizing POM. This is Ph.D. thesis research by Antonio Martinez that is close to completion. The separate effects of forcing by winds and by coastal-trapped waves incident from the south have been examined. A relatively high resolution grid (3 km horizontal grid size, 50 sigma levels in the vertical) has been employed to adequately resolve the mesoscale flow. The wind forcing experiments have been run for 240 days (August 1996 - March 1997). The model results are analyzed for the last 120 day period. The wind stress is obtained from a combined product of scatterometer measurements and NCEP analyses. The wind-forced surface currents flow out of the gulf during the strong wind season (December-March), while the average currents at depth flow into the gulf. This feature is consistent with observations and helps explain the high productivity in the gulf. The most striking new feature of the wind-forced circulation is the formation of eddies in the south and central gulf. The scale of these eddies is about 90 km and they are generated on both sides of the gulf. The coastal-trapped wave experiments have been run for an 80 day period 1 July - 19 September 1984 during which time extensive current and hydrographic measurements were made in the gulf. These measurements are utilized for model/data comparisons. The incident coastal-trapped waves are assumed to have the spatial structure of the first baroclinic linear mode with time variability given by coastal sea level measurements at Acapulco. These waves propagate northward into the gulf along the coast of mainland Mexico. Typical periods of the energetic events are 5 to 7 days. Along the mainland shore of the gulf, the waves lose some energy due to topographic irregularities of the main basins of the gulf. After the waves reach the sill, where the depth decreases abruptly from 1500m to 200m, a small fraction of the energy continues north where it is dissipated in the shallower water. Most of the energy is reflected at the sill as a wave that travels south along the coast of the Baja Peninsula. The wave that leaves the gulf on the Baja side contains only a small fraction of the incident energy. In addition, a series of process-oriented experiments have been pursued to better understand coastal-trapped wave propagation in the gulf. In these experiments, the behavior of idealized incident wave pulses, with varying wavelengths and amplitudes, have been studied. It is found that, with amplitudes of realistic magnitude (e.g., sea level disturbances of 20 cm), nonlinear effects result in appreciable wave steepening and in differing behavior of sea level elevation and depression pulses. These effects play an important role in the wave evolution in the gulf.

## PUBLICATIONS

Papers, published and submitted, that include research results produced with primary or partial support from this grant.

- 1995 Upwelling circulation on the Oregon continental shelf: Part 1: response to idealized forcing, *J. Phys. Oceanogr.*, 25:1843-1866 (J. S. Allen, P. A. Newberger, J. Federiuk)  
Upwelling circulation on the Oregon continental shelf: Part 2: simulations and comparisons with observations. *J. Phys. Oceanogr.*, 25:1867-1889 (J. Federiuk, J. S. Allen)
- 1996 Nonlinear shear instabilities of alongshore currents on plane beaches, *J. Fluid Mech.*, 310:181-213 (J. S. Allen, P. A. Newberger, R. A. Holman)  
Downwelling circulation on the Oregon continental shelf: Part 1, response to idealized forcing, *J. Phys. Oceanogr.*, 26:2011-2035 (J. S. Allen, P. A. Newberger)  
Model studies of near-inertial waves in flow over the Oregon continental shelf, *J. Phys. Oceanogr.*, 26:2053-2075 (J. Federiuk, J. S. Allen)  
On the use of the Boussinesq Equations, the Reduced System, and the Primitive Equations for the computation of geophysical flows, *Dyn. Atmos. Oceans*, 25:1-24 (P. A. Newberger, J. S. Allen)  
Extended-geostrophic Hamiltonian models for rotating shallow water motion, *Physica D*, 98:229-248 (J. S. Allen, D. D. Holm)
- 1997 A Note on Kelvin waves in balance models, *J. Phys. Oceanogr.*, 27:2060-2063 (J. S. Allen, P. R. Gent, D. D. Holm)
- 1998 On symmetric instabilities in oceanic bottom boundary layers, *J. Phys. Oceanogr.*, 28:1131-1151 (J. S. Allen, P. A. Newberger)  
Nonlinear shear instabilities of alongshore currents over barred beaches, *J. Geophys. Res.*, 103:18,357-18,379 (D. N. Slinn, J. S. Allen, P. A. Newberger, R. A. Holman)
- 2000 Alongshore currents over variable beach topography, *J. Geophys. Res.*, 105:16,971-16,998 (D. N. Slinn, J. S. Allen, R. A. Holman)  
Assimilation of surface current measurements in a coastal ocean model, *J. Phys. Oceanogr.*, 30:2359-2378 (R. K. Scott, J. S. Allen, G. D. Egbert, R. N. Miller)  
Diagnosis of the three-dimensional circulation in mesoscale features with large Rossby number, *J. Phys. Oceanogr.*, 30, 2687-2709 (R. K. Shearman, J. A. Barth, J. S. Allen, R. L. Haney)  
Modeling studies of the coastal circulation off northern California: shelf response to a major Eel River flood event, *Continental Shelf Res.*, 20,2213-2238 (J. D. Pullen, J. S. Allen)
- 2001 Modeling studies of the coastal circulation off northern California: statistics and patterns of wintertime flow, *J. Geophys. Res.*, 106:26,959-26,984 (J. D. Pullen, J. S. Allen)
- 2002 Extended-geostrophic Euler-Poincare models for mesoscale oceanographic flow, *Large-scale atmosphere-ocean dynamics*, Cambridge University Press, in press (J. S. Allen, D. D. Holm, P. A. Newberger)  
Analysis and comparison of three ecosystem models, *J. Geophys. Res.*, submitted (P. A. Newberger, J. S. Allen, Y. H. Spitz)  
Ecosystem response to upwelling off the Oregon coast: Behavior of three nitrogen-based models, *J. Geophys. Res.*, submitted (Y. H. Spitz, P. A. Newberger, J. S. Allen)  
Modeling study of turbulent mixing over the continental shelf: Comparison of turbulent closure schemes, *J. Geophys. Res.*, submitted (H. W. Wijesekera, J. S. Allen, P. A. Newberger)